SULPHUR DIOXIDE DETECTION METHOD

Field of the Invention

5   The invention relates to a sulphur dioxide
detection method and apparatus.

Background to the Invention

10   Volcanic ash and sulphur dioxide clouds
constitute a serious hazard to aircraft even after the
clouds have moved from the site of a volcanic eruption.
Apart from containing ash particles, the clouds include
gases such as SO_2 which after a few days oxidises and
15   hydrolises to form sulphuric acid droplets, either as an
ash-acid mixture or as a coating over ash particles. Both
the ash particles and the sulphuric acid droplets of
volcanic ash clouds are capable of causing significant
damage to and possible loss of an aircraft which
20   encounters an ash cloud.

          A number of aircraft encounters with volcanic ash
clouds or sulphur dioxide clouds have been recorded in the
past where significant damage has occurred. It will be
25   appreciated that the sulphur dioxide may be found in areas
separate from the volcanic ash. In the year 2000, a
National Aeronautics and Space Administration (NASA) DC-8
Airborne Sciences research airplane flew through what was
described as a diffuse volcanic ash cloud from the mount
30   HEKLA Volcano when flying from Edwards, California to
Kiruna, Sweden. The ash cloud was not visible to flight
crew, however, the research airplane carried sensitive
research equipment which was capable of detecting the
sulphur dioxide. In-flight checks and post-flight visual
35   inspections revealed no damage to the airplane. However,
detailed examination of the engines revealed damage to
some of the turbine cooling passages. Furthermore, high

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levels of sulphur were found in the oil.

It seems likely that this ash cloud actually was predominantly a sulphur dioxide cloud. Even if it was
5   not, it raises the possibility that an aircraft can fly through sulphur dioxide without passing through ash. The post encounter treatment of the engine in the case of sulphur dioxide encounter would be different to and considerably cheaper than the equivalent treatment
10   required of an engine during an ash encounter.

Accordingly, it would be desirable to provide a sulphur dioxide cloud detection technique.

15   **Summary of the Invention**

The present invention relates to a method of detecting sulphur dioxide clouds comprising:
measuring infrared radiation at a viewing elevation
20   at or above the horizon and at a key wavelength at which there is a sulphur dioxide feature and in the vicinity of which there is a region where the amount of infrared radiation from water vapour in the atmosphere varies in accordance with a predetermined relationship;
25   measuring radiation at two or more subsidiary wavelengths in said region;
determining the amount of radiation from water vapour at the key wavelength from the measured radiation at the subsidiary wavelengths using the predetermined
30   relationship; and
determining whether a sulphur dioxide cloud is present from the measured infrared radiation at the key wavelength and the determined amount of radiation from water vapour.
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Preferably, said subsidiary wavelengths are located either side of said key wavelength.

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The inventor has determined that the key
wavelength should be one of 7.3μm and 8.6μm and that 7.3μm
is the preferred key wavelength.

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Where the key wavelength is 7.3μm, it is
preferred that subsidiary wavelengths at ±0.5μm are used.
The inventor has established that for the region of these
wavelengths the predetermined relationship is that
10 radiation from water vapour varies in a substantially
linear manner. Accordingly, the radiation from water
vapour at the key wavelength can be interpolated from the
radiation at the subsidiary wavelengths on the basis of
this predetermined relationship. The inventor has also
15 established that there is substantially less SO_2 absorption
at this wavelength.

The method may also involve compensating for
background SO_2 in the atmosphere.

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The invention also provides a detection apparatus
for detecting a sulphur dioxide cloud comprising:
measurement means that measures infrared
radiation at a viewing elevation at just below, or above
25 the horizon and at a key wavelength at which there is a
sulphur dioxide feature and in the vicinity of which there
is a region where the amount of infrared radiation from
water vapour in the atmosphere varies in accordance with a
predetermined relationship, said measurement means also
30 measuring infrared radiation at two or more subsidiary
wavelengths in said region; and
processing means for determining the amount of
radiation from water vapour at the key wavelength from the
measured radiation at the subsidiary wavelengths using the
35 predetermined relationship and determining whether a
sulphur dioxide cloud is present from the measured
infrared radiation at the key wavelength and the

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determined amount of radiation from water vapour; and

output means for generating an output signal indicative of the presence of a sulphur dioxide cloud when a sulphur dioxide cloud is present.

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The inventor has also determined that the method and apparatus of the present invention can be used to detect sulphur dioxide clouds from the ground or from an aircraft.

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Brief Description of the Drawings

Figure 1 illustrates the SO_2 absorption feature in the region $1200cm^{-1}$ to $1500cm^{-1}$ and the preferred

15   measurement wavelengths of the invention;

Figure 2 is a schematic diagram of a SO_2 detection apparatus of the preferred embodiment;

Figure 3 illustrates two modes of operation of the apparatus;

20   Figure 4 is a schematic diagram of apparatus to be used from an aircraft;

Figures 5a - 5c represent normal climatic conditions;

Figures 6a and 6b represent variations on normal

25   conditions to allow testing of the invention;

Figure 7 represents variations in SO_2 for testing;

Figure 8 shows variation in temperature with SO_2 concentration; and

30   Figure 9 shows temperature plotted as a function of absorber amount.

Description of the Preferred Embodiment

35   Herein, the term "key wavelength" is used to refer to a wavelength at which there is an appropriate SO_2 feature.

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Persons skilled in the art will appreciate that a "wavelength" in the context of this specification does not imply a single wavelength but rather encompasses a band of
5   radiation. Typically the width of the band will depend on the filter used to observe/measure light at the wavelength of interest. The numerical figures given in this specification are used to denote, in general terms, the centre of such bands, however, it will be appreciated by
10   persons skilled in the art that some variation of the centre wavelength is possible.

The term "subsidiary wavelength" is used to refer to a wavelength in a region in the vicinity of the key
15   wavelength where a relationship can be established between radiation from water vapour at two or more subsidiary wavelengths and radiation from water vapour at the key wavelength.

20   The preferred embodiment provides a method and apparatus that allows identification of sulphur dioxide clouds in the free atmosphere. The apparatus of the preferred embodiment uses an infrared detector, interference filters and focussing optics. The filters
25   divide radiation within the band between 6.8 and 8.1 μm into three narrow bands. The central band corresponds to a strong SO_2 absorption feature caused by the anti-symmetric stretch of the SO_2 molecule at 7.3 μm. The other bands are above and below this feature. The central band
30   B_c, is sensitive to SO_2 concentrations. The lower band, B_l and higher band B_h, are used to account for the effects of water vapour on the absorption in band B_c.

Accordingly, B_c is the key wavelength and B_l and
35   B_h are the subsidiary wavelengths in the preferred embodiment.

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Figure 1 illustrates the absorption feature due
to SO_2 for the infrared region extending from 1200 cm^{-1}
(8.33 μm) to 1500 cm^{-1} (6.67 μm). The ordinate in this
plot is line strength and the abscissa is wavenumber (cm^{-1};
5   wavelength in μm = 10,000/wavenumber in cm^{-1}). Also, shown
are three idealised filter response functions which
isolate radiation within the three narrow regions
corresponding to: B_h (7.633-8.065 μm) B_o (7.143-7.57 μm)
and B_l (6.897-7.042 μm).
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The response functions are normalised to unity
and scaled appropriately for plotting. The central
wavenumber for the SO_2 absorption is 1363 cm^{-1} and the band
extends from about 1320 cm^{-1} to about 1390 cm^{-1}. A filter
15   covering this region responds to all the radiation from
this band; whether the SO_2 feature be due to absorption or
emission. In the case of a detection apparatus viewing a
cold background, i.e. viewing from the ground to space or
from an aircraft towards the horizon, there would be more
20   radiation in this band in the presence of the SO_2 cloud
than if it were absent.

In practice, water vapour and clouds also absorb
and emit radiation in the region 7-8 μm. The inventor has
25   realised that the two bands positioned either side of the
central band can be used to eliminate the effects of water
vapour.

Water vapour absorbs and emits radiation
30   throughout the region 7-8 μm. The amount of radiation
absorbed or emitted depends on the amount of water vapour
and on its location in the atmospheric column. Water
vapour near the boundary of the earth's surface is
generally warm and abundant. Water vapour near the
35   tropopause (i.e. at jet aircraft cruising altitudes) is
cold and sparse. The central band B_o of the SO_2 detector
of the preferred embodiment responds to radiation due to

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both SO_2 and water vapour. The lower and higher bands B_c, B_h of the detector however, are only sensitive to water vapour. The inventor has determined that the radiation from water vapour in the region surrounding B_c behaves in a
5   sufficiently linear manner to enable it to eliminate the effects of water vapour on the central band sufficiently for the purpose of detecting a sulphur dioxide cloud. The Planck blackbody radiation from B_l and B_h are linearly interpolated to estimate the radiation detected in B_c due
10   to water vapour only. This radiation amount is subtracted from the radiation actually measured by B_c. The residual amount is due to SO_2. Accordingly the preferred embodiment utilises a predetermined relationship that water vapour behaves in a linear manner. Persons skilled in the art
15   will appreciate that other predetermined relationships could be used, for example, relationships that are approximately linear.

          A schematic of the detection apparatus is shown
20   for illustrative purposes in Figure 2. The detection apparatus 6 consists of four major components:
   • Fore-optics 1 that focus a beam of incoming infrared radiation onto a detector.
   • A filter wheel 2 consisting of at least three narrow
25   band interference filters that isolate radiation into the bands: B_l, B_c and B_h.
   • An infrared detector array 3 sensitive to radiation in the 7-8 μm region.
   • Processing means 4 for processing the detector signal
30   to determine whether SO_2 and hence a sulphur dioxide cloud is present.

          Figure 3 is a schematic diagram illustrating two modes of operation of a detection apparatus 6 that senses
35   infrared radiation in order to detect SO_2 clouds. A first mode assumes that the detection apparatus 6 is on board an aircraft 7 and views the SO_2 cloud ahead at a small angle

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to the horizontal. The second mode assumes that the
detection apparatus 6 is based on the ground and views the
cloud at a large angle to the horizontal (e.g. zenith
viewing).

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The detection apparatus of the preferred
embodiment may be operated from the ground viewing the sky
above or from an aircraft viewing forwards at just below
or above the horizon. The principal mode of operation is

10   anticipated to be from an aircraft with the instrument
having an unobstructed view of the atmosphere ahead of the
aircraft as the inventor has established that the method
works best when water vapour path amount is less than
$1g\ cm^{-2}$. For example, at heights over 3000 m or in dry

15   atmosphere water vapour path is defined as the integral of
the water vapour concentration with distance along the
line of sight between instrument and target. Ideally the
view should be horizontal or a few degrees (3-5°) above the
horizon, so that the background radiation is cold.

20   Typically, aircraft fly with their nose at an angle of
about 3 degrees to horizontal. However, the processor 4
can be configured to account for changes in viewing zenith
angle, making the technique insensitive to the viewing
direction. For the case of a detection apparatus 6

25   viewing ahead of an aircraft at a zenith angle of Z
degrees, the detection apparatus 6 provides three signals
to the processor 4. A synthetic signal corresponding to
the amount of radiation from water vapour is determined
through linear interpolation of the signals from B_l and B_h.

30   This signal labeled $\hat{B}_c$ is compared to the signal from B_c.

The processor 4 then computes the SO_2 amount at
the key wavelength B_c using $\hat{B}_c$ and the original signal B_c.
The processor 4 uses pre-defined look-up tables that

35   account for standard atmospheric conditions (tropical,
mid-latitude, and polar) and the viewing geometry to
compensate for background SO_2. The detector array 3

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provides an image of the SO_2 amount with a spatial
resolution that depends on the exact number of detector
elements in the array (320x240 is recommended) and the
distance to the SO_2 cloud. Distance information is
5   supplied by the detection apparatus 6, however, the SO_2
anomaly will be detected at distances of up to several 100
kms depending on the cruising altitude and clarity of the
atmosphere ahead. The detection apparatus 6 produces an
output 5, for example in the form of an amount of SO_2 or an
10   alarm signal indicating the presence of sufficient SO_2 to
pose a problem. The alarm signal may cause an audible or
visual alarm in an aircraft.

        Figure 4 illustrates how the apparatus works in
15   the case of being mounted in an aircraft.

        In addition to signals from the detector 3 the
processor 4 also receives aircraft altitude information 8
from the aircraft and standard atmosphere information 9
20   from a memory associated with the processor.

Examples

        A sophisticated radiative transfer model-MODTRAN
25   (Berk, et al., 1989) is used to model the response
expected from a single-element detector viewing arealistic
atmosphere. The viewing geometry is varied in the
simulations to account for viewing from below the SO_2
cloud, viewing from above, and viewing at a small angle
30   along a nearly horizontal path. The amount of SO_2 is
varied, as is the main other gaseous absorber in the
region-water vapour. We refer to the amount of SO_2 as the
cloud thickness.

35   1.   Model Atmosphere

        Vertical profiles of the model atmosphere used in

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the simulations are shown in Figure 5 and variations used
to test the present invention are shown in Figure 6 and
Figure 7.

5   (a)   *Temperature*

The temperature profile is shown in Figure 6a.
Varying the profile has little effect on the retrieval and
detection algorithm because the algorithm uses differences
10   in temperatures. No further simulations were performed on
this parameter because of its insensitivity.

(b)   *Water vapour*

15   Water vapour was varied by increasing the amounts
in the lowest layers from less than 0.1 cm of precipitable
water to more than 3 cm. No effect was found on the
detection or retrieval because the water vapour lies below
the SO_2 cloud. Water vapour was also increased in the
20   layer that contained the SO_2 and this has a major effect.
The perturbed water vapour profile is shown in Figure 6b.

(c) Sulphur dioxide

25   The vertical profile of the background SO_2 is
taken from the US standard atmosphere. The profile
corresponds to a well-mixed gas with a constant vertical
concentration of 10^{-5} ppmV (parts per million by volume).
Perturbed profiles, with increasing SO_2 concentration, are
30   shown in Figure 7. Eight profiles are shown. The
integrated amount of SO_2 in a vertical column for the
profiles varies from 10 milli atm-cm to 100 milli atm-cm.
Depending on the pathlength travelled the total absorber
amount can be much larger. Results for SO_2 absorber
35   amounts of more than 1000 milli atm-cm are given.

2. Viewing the SO_2 cloud along horizontal paths

For the purpose of example, model simulations have been
performed for the case of horizontal viewing from a
platform (e.g. an aircraft) directly ahead and towards an
5   SO_2 cloud. The viewing direction is assumed to be
horizontal at the altitude of the platform (8 km, or
$\approx 26,000$ feet is assumed). The cloud thickness (as
measured in the viewing direction) is varied from 10 km to
500 km and the concentration within the cloud is varied
10   from background levels to ≈ 0.1 ppmV. This range of
concentration covers the smallest eruptions (that are
likely to reach these heights, e.g. Hekla-style eruptions)
to the largest observed this century (e.g. Pinatubo-style
eruptions). The results of these model simulations are
15   summarised in two figures. Figure 8 shows the variation
of the temperature anomaly (the temperature difference
between the synthetic signal and the measured signal as a
function of cloud thickness).

20   The family of curves 20-27 generated from the
modelling are lines of constant concentration for SO_2
concentration varying from 0.0136 ppmV 20 to 0.1083 ppmV
27. The points that lie on vertical lines correspond to
lines of constant cloud thickness. As the cloud thickens
25   the curves follow the same trend with increasing anomalous
signal until the cloud starts to become opaque. At this
point, which varies with SO_2 concentration, the temperature
anomaly increases towards a limiting value ($\Delta T \approx -2$ K).
Note that the opaque limit is reached either by increasing
30   concentration or increasing cloud thickness, since both
quantities increase optical depth and hence absorption.
Beyond a thickness of 500 km, the cloud is essentially
opaque and the radiative process changes from absorption
to emission.
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          Figure 9 provides an alternate way of
understanding the physical processes involved in SO_2

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detection. Here the temperature anomaly is plotted as a function of absorber amount. The plot indicates that for a given anomaly, several values of absorber amount are possible, depending on the cloud thickness and

5   concentration. Thus, it is not possible to uniquely quantify the absorber amount from the temperature anomaly without knowing either the concentration or the cloud thickness. In practice it is not necessary to know these quantities, as the purpose of the invention is to detect

10   the presence of SO_2 gas in the free atmosphere, rather than quantify the amount. The modelling does give an indication of the limits within which detection of SO_2 is possible. At the lower end, for cloud thicknesses of 10 km or less, the SO_2 concentration must be larger than ≈ 0.06

15   ppmV. This corresponds to an absorber amount of ≈ 25 milli atm-cm. SO_2 clouds that intercept air-routes (i.e. heights >20,000 feet) will have horizontal dimensions of 10's of kilometres and absorber amounts well in excess of 25 milli atm-cm would be expected.

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Persons skilled in the art will appreciate that various modifications may be made to the preferred embodiment without departing from the scope of the appended claims.